Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 16 March 2009 (MN LATEX style file v2.2)

The use of OH "main" lines to constrain the variation of fundamental constants

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Received mmddyy/ accepted mmddyy

ABSTRACT
We describe a new technique to measure variations in the fundamental parameters α and $y \equiv m_e/m_p$, using the sum of the frequencies of cm-wave OH "main" lines. The technique is $\sim$ three orders of magnitude more sensitive than that of Chengalur & Kanekar (2003), which utilised only the four 18cm OH lines. The increase in sensitivity stems from the use of OH "main" lines arising from different rotational states, instead of the frequency difference between lines from the same state. We also show that redshifts of the main OH 18cm and 6cm lines can be combined with the redshift of an HCO^+ transition to measure any evolution in α and y. Both 18cm main lines and a number of HCO^+ lines have already been detected in absorption in four cosmologically distant systems; the detection of the main 6cm OH line in any of these systems would thus be sufficient to simultaneously constrain changes in α and y between the absorption redshift and today.

Key words: Line: profiles – techniques: spectroscopic – radio lines

1 INTRODUCTION

In recent times, quasar absorption lines have emerged as an excellent probe of changes in the values of the fundamental "constants" (e.g. Webb et al. 1999; Carilli et al. 2000; Ivanchik et al. 2003). Such variations are expected in theories like extra-dimensional Kaluza-Klein models or super-string theories, where values of the coupling parameters such as the fine structure constant α or the gravitational constant G depend on the expectation values of some cosmological scalar field(s); changes in these parameters are thus to be expected if the latter varies with space and/or time. Various experimental and observational bounds are available on the temporal evolution of different coupling constants: these include the fine structure constant, α (Ivanchik et al. 1999; Webb et al. 2001), the gravitational constant G (Teller 1948; Damour & Taylor 1991), the combination $g_p\alpha^2$ (where g_p is the proton g-factor; Drinkwater et al. 1998; Carilli et al. 2000), the ratio of electron mass to proton mass $y \equiv m_e/m_p$ (Ivanchik et al. 2003), etc. Uzan (2003) provides a review of the available measurements.

The most interesting of the new astrophysical estimates are the recent work of Webb et al. (1999, 2001) who claim a detection of changes in the numerical value of the fine structure constant α between high redshift, $z \sim 3.5$, and the present epoch. The authors initially applied a new 'many-multiplet' method to absorbers with $1 \lesssim z \lesssim 1.6$ to estimate $\Delta\alpha/\alpha = (-1.88 \pm 0.53) \times 10^{-5}$ between redshifts $z \sim 1.6$ and today (Webb et al. 1999). This was followed by the use of this method to estimate $\Delta\alpha/\alpha = (-0.72 \pm 0.18) \times 10^{-5}$ over the redshift range $0.5 < z < 3.5$ (Webb et al. 2001) (see, however, Bekenstein 2003) On the other hand, Ivanchik et al. (2003) constrain the variation in m_e/m_p to be $(3.0 \pm 2.4) \times 10^{-5}$ over a similar redshift range ($0 < z < 3$), comparable to the change claimed in the fine structure constant (albeit using a different absorber sample). This is somewhat surprising, given that most of the above theoretical analyses expect changes in different fundamental constants to be coupled: for example, Calmet & Fritzsch (2002) and Langacker et al. (2002) find that variations in the value of α should be accompanied by much larger changes (by ~ 2 orders of magnitude) in the value of m_e/m_p.

We have recently (Chengalur & Kanekar 2003; hereafter Paper I) demonstrated a new technique to measure (or constrain) changes in the fundamental constants using 18cm OH lines. This method uses the fact that the four OH lines arise from two very different physical phenomena, Λ-doubling and hyperfine structure, and thus have different dependences on the parameters α, y and g_p. Observations of all four OH 18cm transitions in a single cosmologically distant absorber can thus be used to simultaneously estimate variations in y and α, assuming that the proton g-factor remains unchanged (e.g. Webb et al. 2001; Carilli et al. 2000). We have also used the linear relationship between OH

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and HCO^+ column densities observed both in the Milky Way and in four molecular absorbers out to $z \sim 1$ to argue that HCO^+ and OH lines probably arise from the same spatial location and are thus unlikely to have velocity offsets relative to each other. The OH 18cm redshifts can then be combined with the redshift of a single HCO^+ line to simultaneously estimate changes in all three fundamental parameters α, g_p and y, *in the same object*.

A problem with the above approach is that two of the equations used in the analysis (equations (10) and (11) in Paper I) involve the separation of two line frequencies. The four 18cm lines have rest frequencies of 1665.4018 MHz and 1667.3590 MHz ("main" lines, with $\Delta F = 0$), and 1612.2310 MHz and 1720.5299 MHz ("satellite" lines, with $\Delta F = 1$). The separation between the main line frequencies is a factor of ~ 1600 smaller than the sum of these frequencies while the separation between the satellite frequencies is around 30 times smaller than the above sum. This implies that the error on the redshift of the two frequency differences is worse than the error on the redshift of the sum of main line frequencies by the same factors and this large error propagates into the estimates of changes in the values of α, y and g_p. To emphasise this point, we note that the error on the sum of the main line redshifts in B0218+357 is $\sim 5.6 \times 10^{-6}$, while that on the difference between these redshifts is $\sim 6.7 \times 10^{-3}$ (Paper I); it is the latter error that dominates the accuracy of the technique in constraining any changes in the fundamental parameters (and which hence resulted in the large errors in the analysis of the OH, HCO^+ and HI lines from the $z \sim 0.6846$ absorber towards B0218+357 in Paper I).

We describe in this Letter a new approach to simultaneously measure changes in α and y using OH "main" lines arising from different OH rotation states. This is based on the fact that the exact Λ-doubling frequency split depends on the specific quantum numbers of the state in question and has a different dependence on α and y in each state. Since the method only uses the sum of different "main" line frequencies, it is far more sensitive than that discussed above (Paper I), which also uses the difference between pairs of measured frequencies. Further, the sum of OH main line frequencies does not depend on the proton g-factor (as the hyperfine effects cancel out); main lines from any three OH rotation states can thus be used to simultaneously measure changes in y and α. We also show that the main lines from two OH rotation states can be used in conjunction with an HCO^+ transition to simultaneously measure variations in α and y. The use of OH main lines to measure changes in the fundamental constants has also been discussed by Darling (2003); this analysis was, however, based on a simpler approximation to the OH energy levels and also only considered variations in the fine structure constant α.

2 THE SUM OF OH "MAIN" LINE FREQUENCIES

The sum of the "main" line frequencies ν_s in an OH rotation state essentially gives the energy split due to Λ-doubling; this can be written as

$$\nu_s = q_\Lambda \left(J + 1/2\right) \left[\left(2 + \frac{A'}{B'}\right) \left(1 + \frac{2 - A/B}{X}\right) + \frac{4\left(J+3/2\right)\left(J-1/2\right)}{X} \right] \ , \tag{1}$$

where J is the rotational quantum number, A, the fine structure interaction constant and B, the rotation constant (Van Vleck 1929; Townes & Schawlow 1955). The quantity X is defined by

$$X = \pm \left[(A/B) \left\{ (A/B) - 4 \right\} + 4 \left(J + 1/2\right)^2 \right]^{1/2} \ , \tag{2}$$

with the negative sign for the $^2\Pi_{3/2}$ state and the positive sign for the $^2\Pi_{1/2}$ state (Townes & Schawlow 1955). Further, $q_\Lambda \approx 4B^2/h\nu_e$, where $h\nu_e$ is the energy difference between the ground and first excited electronic state. Numerically, $A/B = -7.547$ and $A'/B' = -6.073$ (Townes & Schawlow 1955). The above quantities have the following dependences on the fundamental constants α, y and R_∞ : $A' \propto A \propto \alpha^2 R_\infty$, $B' \propto B \propto y R_\infty$, where R_∞ is the Rydberg constant. For the rotation constant B, we have assumed, as usual (e.g. Murphy et al. 2001), that variations in (m_p/M), which are suppressed by a factor $m_p/U \sim 100$ (where M is the reduced mass and U the binding energy) can be ignored. We thus have $[A'/B'] \propto [A/B] \propto \left(\alpha^2/y\right)$. Finally, we note that equation (1) does not depend on the proton g-factor g_p.

Replacing the above scalings in equation (1) for ν_s, we obtain $\nu_s \propto y^2 R_\infty F\left(\alpha^2/y\right)$, where $F \equiv F\left(\beta\right)$ is a function which depends only on the ratio $\beta \equiv A/B \propto \alpha^2/y$ and is defined by

$$F\left(\beta\right) = \left[\left(2 + \frac{6.073}{7.547}\beta\right) \left(1 + \frac{2-\beta}{X\left(\beta\right)}\right) + \frac{4\left(J+3/2\right)\left(J-1/2\right)}{X\left(\beta\right)} \right] \ . \tag{3}$$

Thus, the ratio of the change in the sum of any two main line frequencies $\Delta\nu_s$ to their sum today is given by

$$\frac{\Delta\nu_s}{\nu_s} = 2\frac{\Delta y}{y} + \frac{\Delta R_\infty}{R_\infty} + \frac{\Delta F\left(\beta\right)}{F\left(\beta\right)} \tag{4}$$

$$= 2\frac{\Delta y}{y} + \frac{\Delta R_\infty}{R_\infty} + \frac{\beta}{F}\frac{dF}{d\beta}\left[2\frac{\Delta\alpha}{\alpha} - \frac{\Delta y}{y}\right] \tag{5}$$

where $$\frac{dF}{d\beta} = C\left(1 + \frac{2-\beta}{X}\right) - \frac{2 + C\beta}{X}\left[1 + \frac{2-\beta}{X}\frac{dX}{d\beta}\right] - \frac{4\left(J+3/2\right)\left(J-1/2\right)}{X^2}\frac{dX}{d\beta} \ . \tag{6}$$

In the above, $dX/d\beta = \left(\beta - 2\right)/X$ and $C = (6.073/7.547)$. Equation (5) has been evaluated for the main lines of the $^2\Pi_{3/2}, J = 3/2$ state in Paper I; we extend this analysis to the main lines of other rotational states that have been detected in the Galactic interstellar medium. The results are listed below, along with the rest frequencies of the "main" lines for each state :

(i) $\mathbf{^2\Pi_{3/2}, J = 3/2}$: Rest frequencies : 1667.3590 and 1665.4018 MHz (i.e. $\sim$ 18cm). Equation (5) yields

$$\frac{\Delta\nu_s}{\nu_s} = 2.571\frac{\Delta y}{y} - 1.141\frac{\Delta\alpha}{\alpha} + \frac{\Delta R_\infty}{R_\infty} \tag{7}$$

(ii) $\mathbf{^2\Pi_{1/2}, J = 1/2}$: This state has a single main line, at a rest frequency of 4750.656 MHz ($\sim$ 6cm); the second main line corresponds to an F = 0–0 transition, which is forbidden by the selection rules. This might appear to be a drawback, since it would seem impossible to detect both main lines. However, it turns out that the frequency separation between the two main lines vanishes, to first order. This can be seen as the separation between the two main line frequencies ν_1 and ν_2 is

$$\Delta\nu \equiv \nu_1 - \nu_2 = \frac{-2d\left(-X - 2 + \beta\right)}{3X} \tag{8}$$

where d is a hyperfine constant (equation (46) of Dousmanis et al. 1955). Further, $X = \beta - 2$ for $J = 1/2$, implying that $\Delta\nu = 0$. Thus, the sum of the two main line frequencies for the $J = 1/2$ case is, to first order, merely equal to twice the F = 1–1 frequency and a detection of this transition is sufficient to measure the above sum. In this case, equation (5) yields

$$\frac{\Delta\nu_s}{\nu_s} = 0.509\frac{\Delta y}{y} + 2.982\frac{\Delta\alpha}{\alpha} + \frac{\Delta R_\infty}{R_\infty} \tag{9}$$

(iii) $\mathbf{^2\Pi_{3/2}, J = 5/2}$: Rest frequencies : 6030.747 MHz and 6035.092 MHz ($\sim$ 5cm). Equation (5) yields

$$\frac{\Delta\nu_s}{\nu_s} = 2.452\frac{\Delta y}{y} - 0.903\frac{\Delta\alpha}{\alpha} + \frac{\Delta R_\infty}{R_\infty} \tag{10}$$

(iv) $\mathbf{^2\Pi_{1/2}, J = 3/2}$: Rest frequencies : 7761.747 MHz and 7820.125 MHz ($\sim$ 3.8cm). Equation (5) yields

$$\frac{\Delta\nu_s}{\nu_s} = 0.072\frac{\Delta y}{y} + 3.857\frac{\Delta\alpha}{\alpha} + \frac{\Delta R_\infty}{R_\infty} \tag{11}$$

(v) $\mathbf{^2\Pi_{1/2}, J = 5/2}$: Rest frequencies : 8135.870 MHz and 8159.587 MHz ($\sim$ 3.7cm). Equation (5) yields

$$\frac{\Delta\nu_s}{\nu_s} = -0.920\frac{\Delta y}{y} + 5.840\frac{\Delta\alpha}{\alpha} + \frac{\Delta R_\infty}{R_\infty} \tag{12}$$

(vi) $\mathbf{^2\Pi_{3/2}, J = 7/2}$: Rest frequencies : 13434.596 MHz and 13441.4173 MHz ($\sim$ 2.2cm). Equation (5) yields

$$\frac{\Delta\nu_s}{\nu_s} = 2.334\frac{\Delta y}{y} - 0.678\frac{\Delta\alpha}{\alpha} + \frac{\Delta R_\infty}{R_\infty} \tag{13}$$

We note that each of the above equations (7 – 13) has the same dependence on the Rydberg constant R_∞, but different dependences on y and α. If we have two transitions whose rest frequencies $\nu_1(0)$ and $\nu_2(0)$ depend on redshift, due to the evolution of various fundamental constants such as α, y, etc, the first order difference between the measured redshifts is (e.g. Paper I)

$$\frac{\Delta z}{1+\bar{z}} = \left[\frac{\Delta\nu_2}{\nu_2(0)}\right] - \left[\frac{\Delta\nu_1}{\nu_1(0)}\right] , \tag{14}$$

where $\bar{z}$ is the mean measured redshift. Given two spectral lines (or linear combinations of line frequencies) with different dependences on some fundamental parameter, the differences between the measured redshifts can be used to constrain the evolution of the parameter in question. Clearly, any three of the equations (7 – 13) can be combined in pairs in equation (14) to yield two simultaneous equations in $\Delta\alpha/\alpha$ and $\Delta y/y$, which can then be solved to measure any changes in both these quantities. Thus, the detection of the "main" OH lines in any three of the OH rotation states in a single absorber can be used to simultaneously measure changes in α and $y \equiv m_e/m_p$ at the same physical space-time location. Note that the large number of OH rotational states allows a simple self-consistency check of any such measurement, by a search for the "main" lines from a fourth OH rotation state. Since this technique uses different lines from the same species, systematic velocity offsets between the different absorption lines are unlikely to be the dominant source of error. It should be noted, however, that the higher OH rotational levels may be excited in regions with very different physical conditions from regions giving rise to OH ground state absorption; the possibility of velocity offsets between the 18cm absorbing gas and the 6cm or 5cm absorbing gas hence cannot be ruled out. However, the OH column density of the absorbing gas can be independently estimated from the different OH lines; if these estimates are found to be in agreement, it would argue that all the lines originated in the same gas cloud.

HCO^+ rotational transitions also have no dependence on the proton g-factor g_p, with line frequencies proportional to yR_∞. Moreover, as discussed in Paper I, the linear relation between HCO^+ and OH column densities observed both in the galaxy (Liszt & Lucas 1996) and out to $z \sim 1$ (Kanekar & Chengalur 2002) (extending over more than two orders of magnitude in column density) suggests that the two species are likely to be located in the same region of a molecular cloud. This implies that one of the OH rotation states in the above analysis can be replaced with an HCO^+ transition. Both 18cm main lines and a number of HCO^+ transitions have already been detected in four molecular absorbers between $z \sim 0.25$ and $z \sim 0.9$ (Wiklind & Combes 1995, 1996a,b, 1997; Chengalur et al. 1999; Kanekar & Chengalur 2002; Kanekar et al. 2003); the detection of a single 6cm "main" line in one of these absorbers (which seems the most promising of the remaining OH main lines) would thus be sufficient to carry out the above measurement. We end this discussion by setting out the two simultaneous

equations obtained by using the 18cm and 6cm main lines and an HCO^+ line in equation (14). Combining the sum of 18cm main line frequencies with the HCO^+ frequency gives

$$\frac{\Delta z_{13}}{1+\bar{z}_{13}} = 1.571\frac{\Delta y}{y} - 1.141\frac{\Delta\alpha}{\alpha} \quad . \tag{15}$$

Similarly, combining the frequencies of the OH 6cm main line with an HCO^+ transition yields

$$\frac{\Delta z_{23}}{1+\bar{z}_{23}} = -0.491\frac{\Delta y}{y} + 2.983\frac{\Delta\alpha}{\alpha} \quad , \tag{16}$$

where $\Delta z_{ij} = z_j - z_i$, $\bar{z}_{ij} = (z_i + z_j)/2$ and the subscripts 1, 2 and 3 denote the 18cm, 6cm and HCO^+ transitions respectively. A detection of the main 6cm OH lines in any of the four cosmologically distant absorbers can thus be immediately used in the above equations to measure $\Delta\alpha/\alpha$ and $\Delta y/y$.

It has been emphasized in the introduction that the primary drawback of our earlier analysis, using the 18cm OH lines (Paper I), is that the frequency separation between the main 18cm lines is only $\sim 1.957/(1+z)$ MHz, where z is the absorption redshift. This dominated the errors in redshift measurements and hence resulted in the large final errors in the analysis of the absorption lines towards B0218+357. Of course, the advantage of this method is that it simultaneously allows a measurement of changes in three fundamental parameters, g_p, α and $y \equiv m_e/m_p$. In the present case, while we have a far higher accuracy in the measurement (as the frequency sum of the 18cm main lines is larger than their frequency difference by a factor of ~ 1600 and by an even higher factor for the higher order transitions), the technique only allows an estimate of changes in α and y. However, these estimates can be replaced in the equation for the separation between the satellite 18cm OH lines (equation (11) in Paper I) to constrain the evolution of the proton g-factor g_p. While this last measurement would be a factor of ~ 30 less sensitive than the measurements of $\Delta\alpha/\alpha$ and $\Delta y/y$, it is still more than 50 times more sensitive than estimates of $\Delta g_p/g_p$ obtained using the earlier method (Paper I); this is due to the fact that the frequency separation between the 18cm satellite lines is $\sim 108/(1+z)$ MHz, fifty times larger than that between the 18cm main lines.

We note, in passing, that other "Lambda-doubled" systems are known to exist in the laboratory and any of these could, in principle, be used in place of OH in a similar calculation. However, to the best of our knowledge, multiple transitions have not been detected in these other systems in astrophysical sources; we suspect that the strength of cm-wave OH lines is likely to make OH the best candidate for such analyses. Further, the present calculation is based on a perturbative treatment of the OH levels (Van Vleck 1929; Townes & Schawlow 1955); more recent analyses (e.g. Brown & Merer 1979) use the "effective Hamiltonian" approach, resulting in higher order effects. As pointed out in Paper I, these are unlikely to significantly affect our results.

Finally, we estimate the accuracy that could be obtained in a measurement of $\Delta\alpha/\alpha$ by the present method, for the $z \sim 0.885$ absorber towards PKS 1830−21; the latter has the highest redshift of all known 18cm OH absorbers (Kanekar & Chengalur 2002). We simplify the analysis by assuming that y is constant, so that main lines of only two rotational states need be used; we will consider the $\mathbf{^2\Pi_{3/2}, J = 3/2}$ and $\mathbf{^2\Pi_{1/2}, J = 1/2}$ states, i.e. main lines at observing frequencies of ~ 885 MHz and ~ 2520 MHz, respectively, for an absorber at $z = 0.885$. Next, a resolution of 2 kHz is not unreasonable for radio spectroscopy with present-generation telescopes. Even if we assume that the line centroids are only determined to this accuracy (i.e. that sub-channel resolution is not obtained, via fitting to the line profile), the errors on the redshifts of the sum of main line frequencies would be $\Delta z = 1 \times 10^{-6}$ and $\Delta z = 4 \times 10^{-7}$, for the 18cm and 6cm lines, respectively. Combining equations (7) and (9) in equation (14) (and assuming y to be constant) then gives $\Delta\alpha/\alpha = 1.5 \times 10^{-7}$, the 1σ accuracy in a measurement of changes in α from $z \sim 0.885$ to today. This is significantly better than the precision obtained in the best optical studies today (e.g. $\Delta\alpha/\alpha = 6 \times 10^{-7}$; Chand et al. (2004)). Note, however, that the above errors do not take into account systematic effects, i.e. the possibility of relative motions between the 18cm and 6cm absorbing clouds; as mentioned earlier, observations of lines from other OH rotational states would help to constrain such systematics.

In summary, we have demonstrated a new technique to simultaneously measure any evolution in two fundamental constants α and $y \equiv m_e/m_p$, using OH "main" absorption lines. The method is $\sim$ three orders of magnitude more sensitive than that described by Chengalur & Kanekar (2003), which utilised the four OH 18cm lines for the analysis. The increase in sensitivity comes from the use of OH "main" lines arising from different OH rotational states, rather than the difference between the frequencies of lines arising from the same state. The technique requires the detection of main lines from three OH rotational states or, alternately, two OH states and one HCO^+ transition, in the same absorber. The large number of OH rotational states also allows a simple consistency check of any measurement by a search for the main lines of one further OH state. Both 18cm main lines and a number of HCO^+ transitions have been detected in absorption in four extra-galactic molecular absorbers. The detection of a single 6cm main line in any of these systems would thus be sufficient to simultaneously measure (or constrain) changes in α and $y \equiv m_e/m_p$.

3 ACKNOWLEDGMENTS

We are grateful to Rajaram Nityananda for very useful discussions on the energy levels of the OH ground state.

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